HTS Fault Current Controller (FCC) Restoration Project

Los Alamos National Laboratory

Joe Waynert, Heinrich Boenig, Chuck Mielke,
Jeffrey Willis, Joe Schillig, Dean Peterson, Brian Newnam,
Larry Bronisz, Ernie Serna, Darrell Roybal, Jim Stewart

Phil Pellegrino, Xing Yuan, Peter Sutherland, ***IGC-SuperPower***

Burt Burley, Alan Langhorne, ***General Atomics***

Andreas Neuber, Heath Keene, ***Texas Tech University***

Peter Gifford, Rich Dishman, ***Cryomech***

FY2002 Project Funding: $500 k
2002 DOE Annual Peer Review
Washington, DC July 17-19, 2002

High-Voltage Breakdown Precluded Completion of 1999 Demonstration Tests of FCC at SCE Substation

SPI ended and DOE contracted with LANL to:

- Evaluate extent of damage
- Repair and modify FCC, if feasible
- Perform high-voltage and integrated FCC tests using Los Alamos 13.7 kV substation

LANL redesign of HV bus leads to successful FCC single-phase tests - June 22, 2002 !!!

Research Integration

Los Alamos (***High power tests, HV bus design, power electronics, control, cryogenic engineering***)

is collaborating with team members:

- **IGC-SuperPower** ***(HTS coils, high power tests, marketing)***
- **General Atomics** ***(Electrical and cryogenic test support)***
- **Texas Tech University** ***(HV insulator tests, HV engineering)***
- **Cryomech, Inc.** ***(Cryogenic systems)***
- **DOE-Golden Office** ***(Program support)***
- **Southern California Edison (SCE)** ***(SPI host utility)***

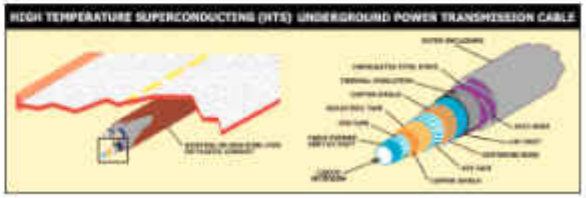
Development & Commercialization of HTS Fault Current Limiting Technologies

Philip J. Pellegrino
President, IGC-SuperPower

2002 Annual Superconductivity Peer Review
Superconductivity Program for Electric Systems, Department of Energy

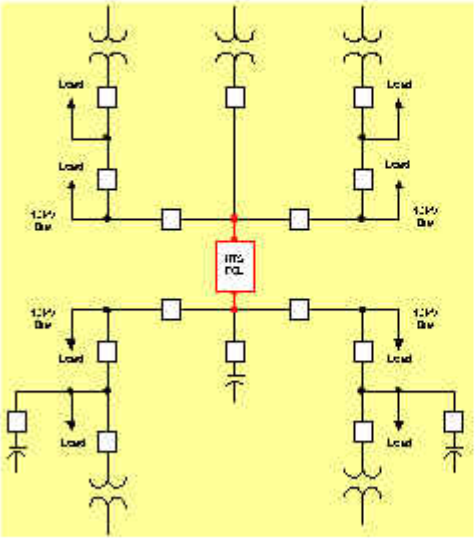
Reliability & Cost Are Two Key Hurdles for Utility Acceptance of HTS Power Devices

- Elements for technology acceptance:
  - Device functionalities validated by vigorous tests under real-world operating scenarios
  - Demonstrated long term reliable operation on an utility grid
- Elements for market acceptance:
  - Demonstrated cost advantage either under direct replacement or life-cycle criteria



Completion of alpha FCC Restoration & Demonstration on Utility Grid Critical for Commercialization

- Single-phase tests successful at LANL
  - Identified and fixed problems
  - Proof of FCC concept
- More needs to be done to demonstrate viability of the technology
  - Three-phase tests
  - Grid operation



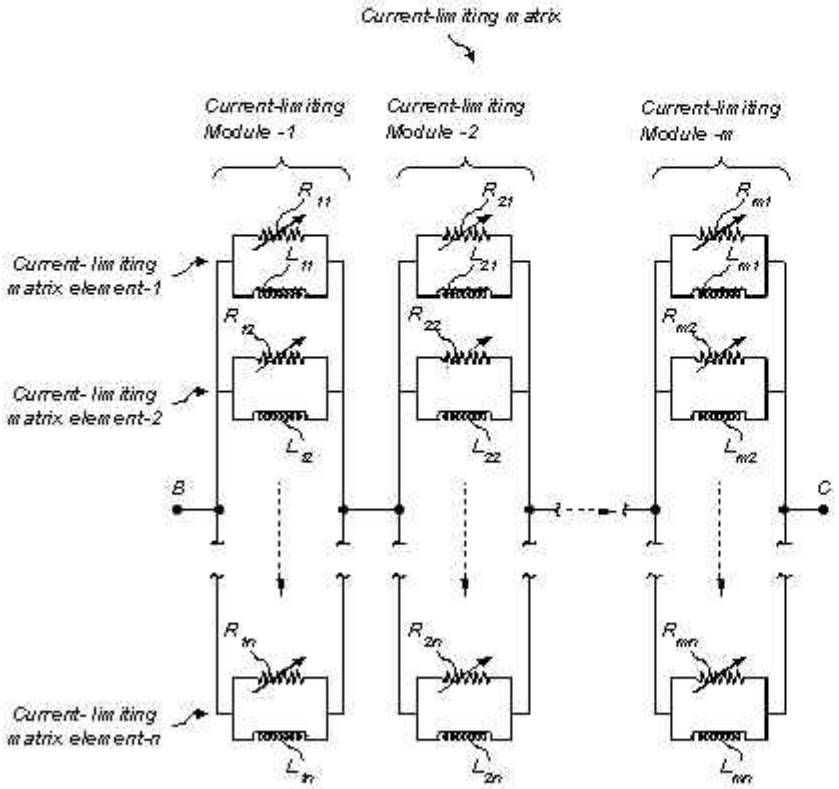
- Several FCC applications identified at distribution substations of a major metropolitan utility
  - Unique technical solutions
  - Significant economic benefit
- The utility decided against installing a beta-FCC, citing lack of test data from alpha FCC and concern of reliability

Successful Grid Demonstration of FCC Prototype Promotes HTS Technology for Power Applications

- DOE should continue to fund the completion of alpha FCC restoration, and test and continuous operation on utility grid
  - Three-phase tests at LANL
  - System tests on utility grid and long term evaluation of continuous operation

- Commercialization of HTS FCC hinges on successful manufacturing of 2nd generation YBCO long-length HTS tape
  - Cost competitiveness
  - Added benefits of low loss and small size (extremely important for urban indoor distribution substations)

IGC-SuperPower Developed Matrix FCL Concept to Address Strong Market Pull for a Transmission-Voltage Fault Current Limiting Device



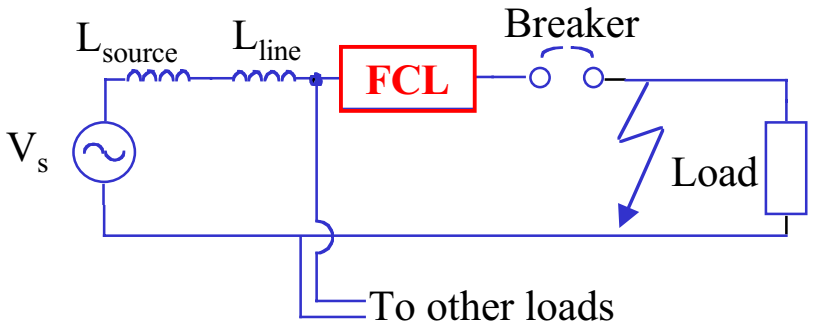
- Passivity
- Transparency
- Modularity and scalability
- Reliability (Redundancy)
- Cost benefit
- Does not depend on coated conductor

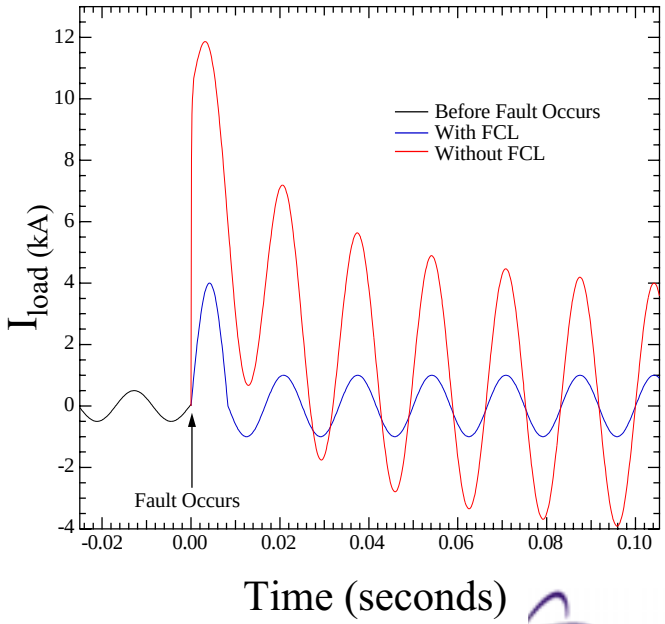
Outline of Talk

- Fault Current Limiter (Controller) Overview
- Approach of Restoration Program
- HV Bus Redesign
- Verification of Control System and Power Electronics Operations
- Cryogenic and Vacuum System
- Single-phase LANL Substation Tests
- Performance/Results/Plans

Fault Current Limiter (FCL) Overview

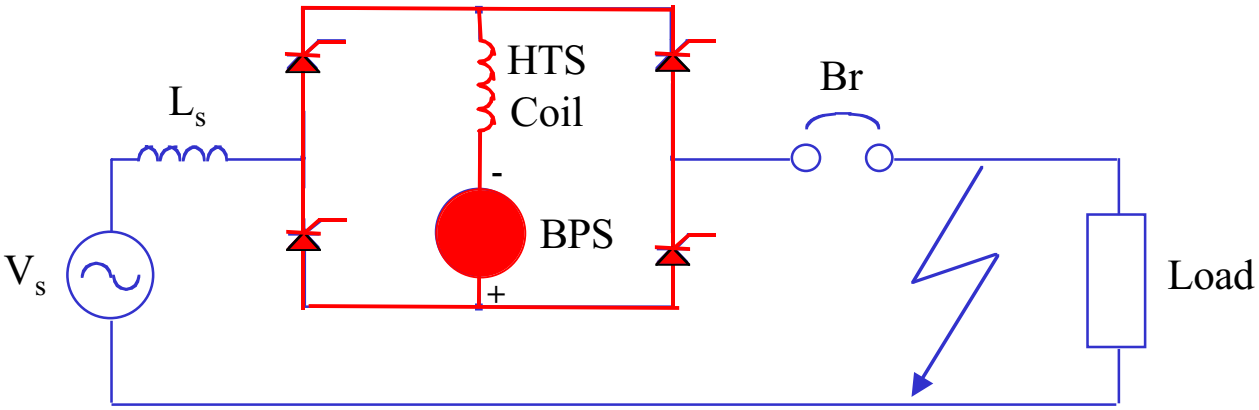
- FCL puts additional impedance in line only during fault (additional impedance limits the current)
- FCL could be an extremely useful network component
- No such device presently exists





Bridge-Type FCL

- More versatile than competing concepts
- Power electronics used for voltage blocking/current limiting
- Bias Power Supply not required
- Compares peak current to DC current

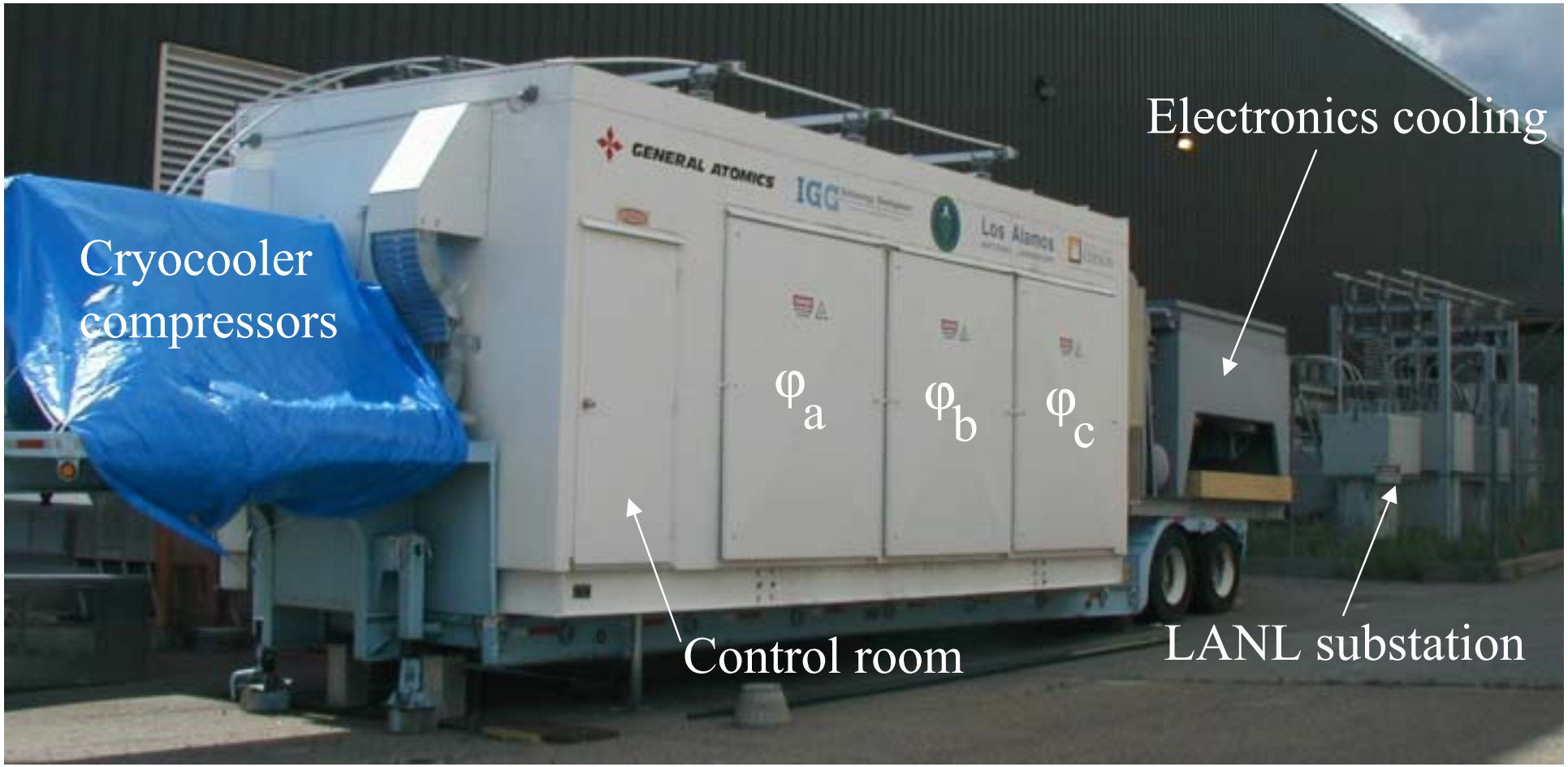


Features of the Bridge-Type FCL

- Steady-state fault current continuously adjustable from zero to peak value - *Fault Current Controller*, **FCC**
- Limits first half cycle of short circuit current
- Can operate as a solid-state breaker in less than a cycle
- Automatically returns to rated operation after fault ceases
- Suitable for multiple reclosures
- Suitable for high power operation

  (Prototype device is rated 15 kV/26 MVA)

FCC Located at Los Alamos Next to the Substation

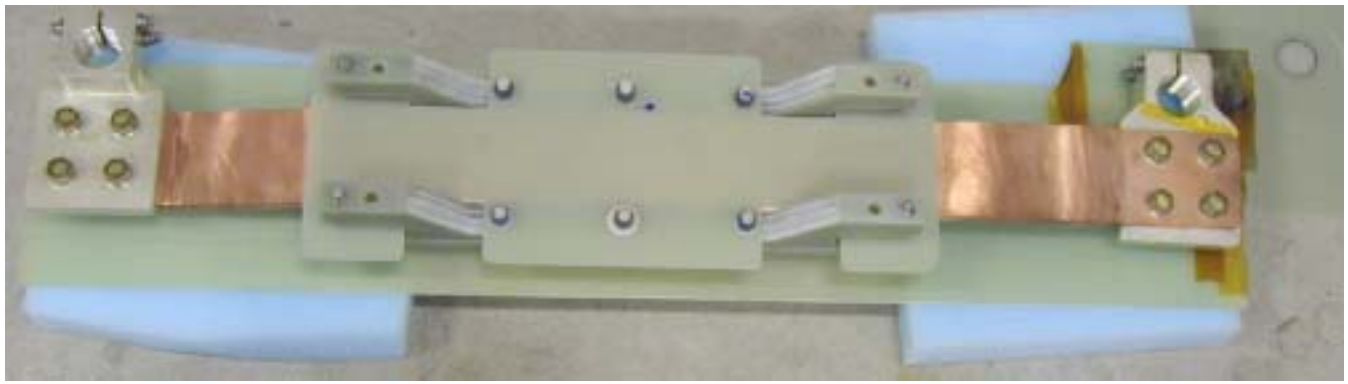


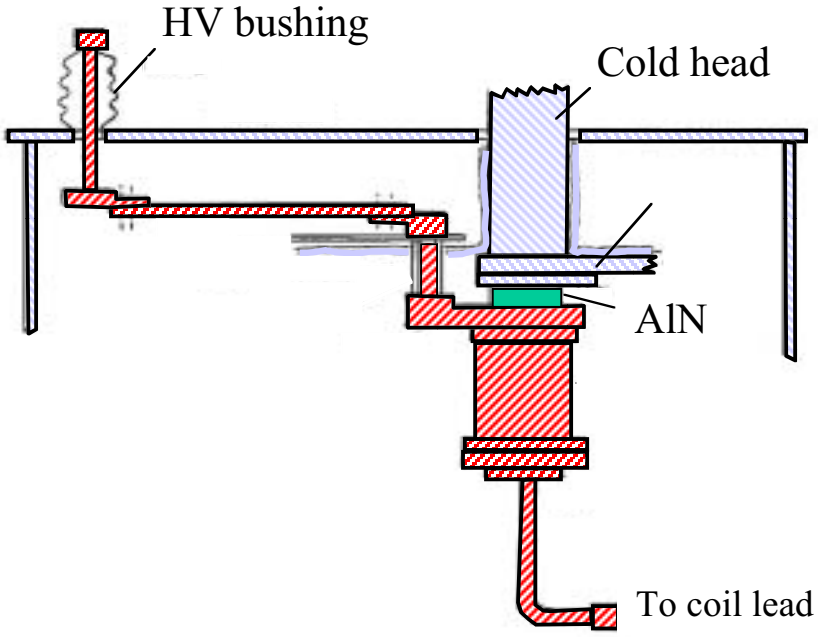
Approach to FCC Restoration

- Analysis of 7/99 SCE test results -

  HTS coils not in circuit during tests
- LANL & DOE agree on cost of FCC restoration (phased approach)
- LANL evaluate extent of damage
  - transport FCC trailer to LANL
  - remove FCC vessels (10/2000) for inspection
  - discovered flashover inside two vessels, outside of third
  - need redesign of HV bus
- Perform single-phase testing at LANL substation

HV Bus Redesign

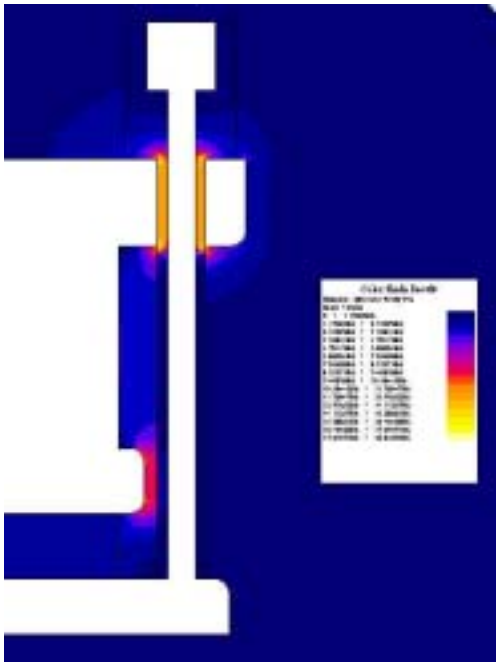




Potential Causes of Voltage Breakdown

- More-obvious causes of voltage flashover
  - Field enhancement by sharp corners
  - Presence of dirt particles
- Less-obvious causes of voltage flashover
  - Voltage doubling by resonance
  - Local gas cloud from ice evaporation
  - MLI evaporation from arcing
  - Reduction of breakdown voltage by magnetic field

New HV Bus Design



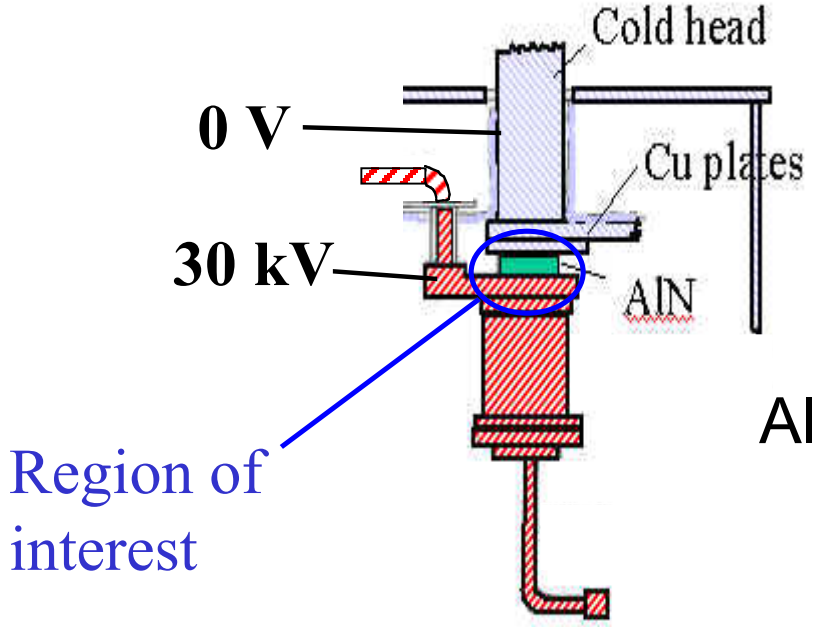
Finite element electrostatics analysis

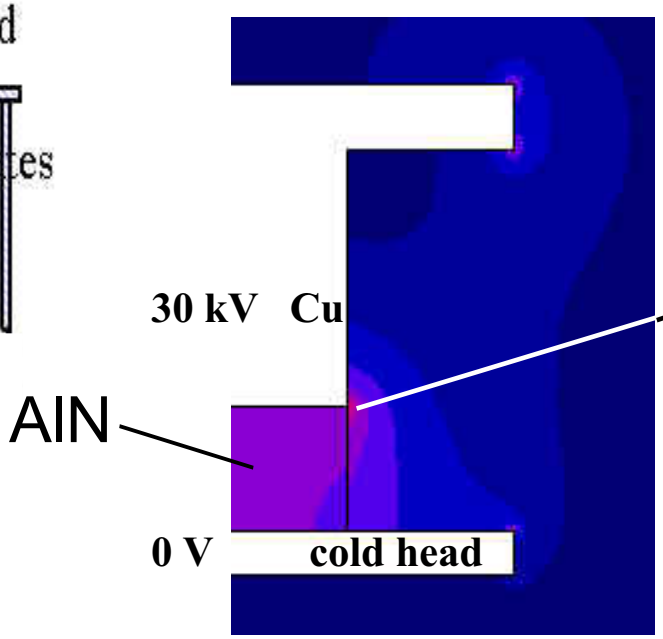
Solid modeling

Prototype fabrication and testing

HV Breakdown - Next Weakest Link - AlN

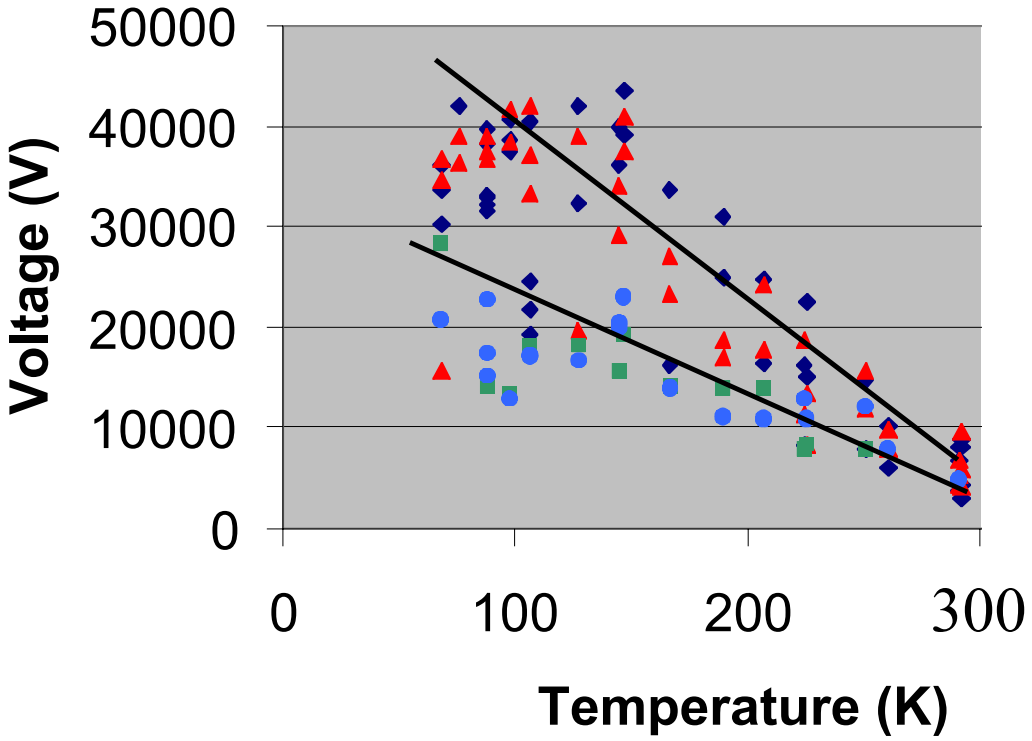
Aluminum nitride (AlN) - electrical isolation, thermal conduction





old design (upside down)

Texas Tech Measures Voltage Breakdown on Aluminum Nitride, AlN

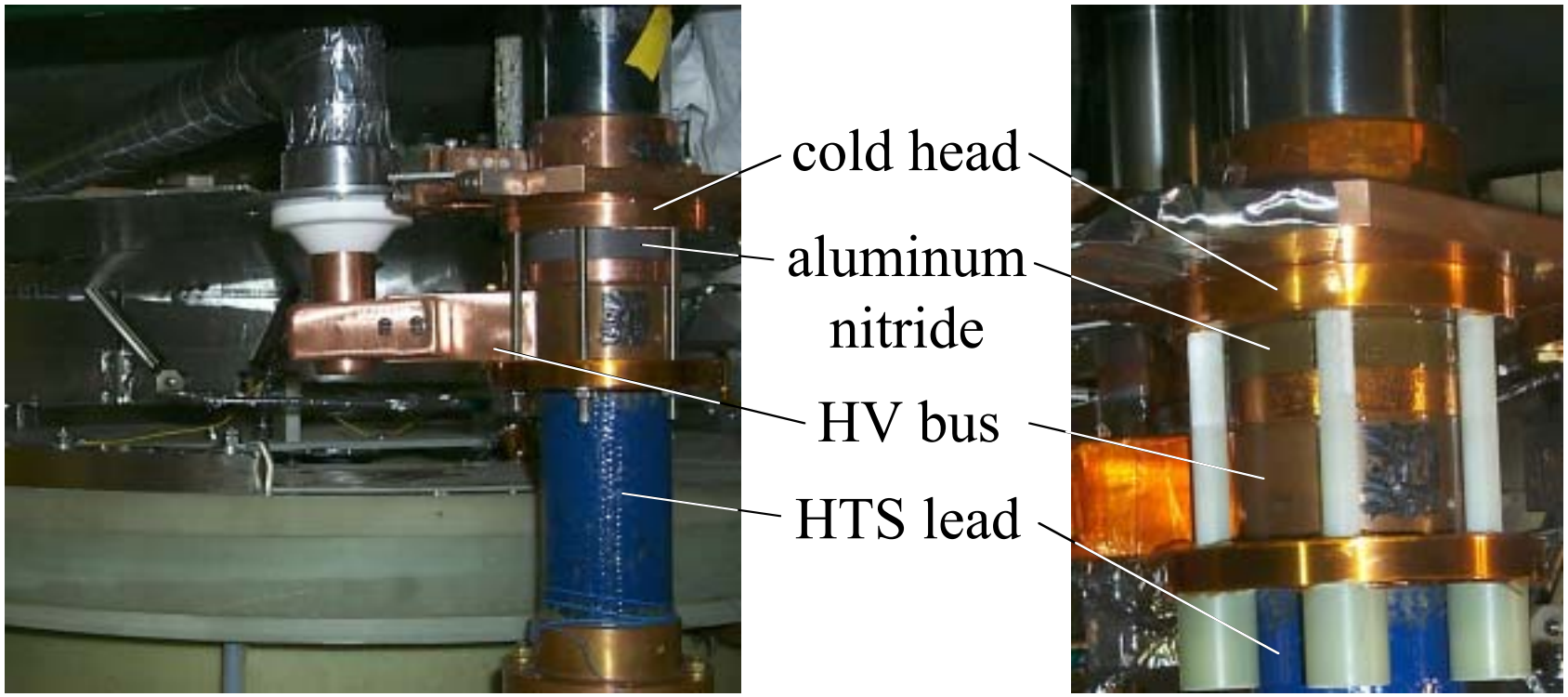


Results to be published in ***IEEE 2002 International Power Modulator Conference***

Installed HV Bus Adequate for LANL Substation Testing

- Fabricate prototypes
- Testing protocol
  - hipot in air, room temperature
  - thermal cycle to LN2 temperature several times
  - visually exam
  - hipot in air, room temperature
  - hipot in vacuum, room temperature
  - hipot in vacuum, temperature gradient (300 K - 40 K)
- Final design selection
  - fab, hipot, install, hipot without AlN (300 K: air and vacuum)
  - install AlN, hipot (300 K: air, vacuum; 40 K vacuum)
- Reconnect HTS coil to bus

Installed HV Bus Hipot Tested to 15 kV



Verification of Control System and Power Electronics Operations

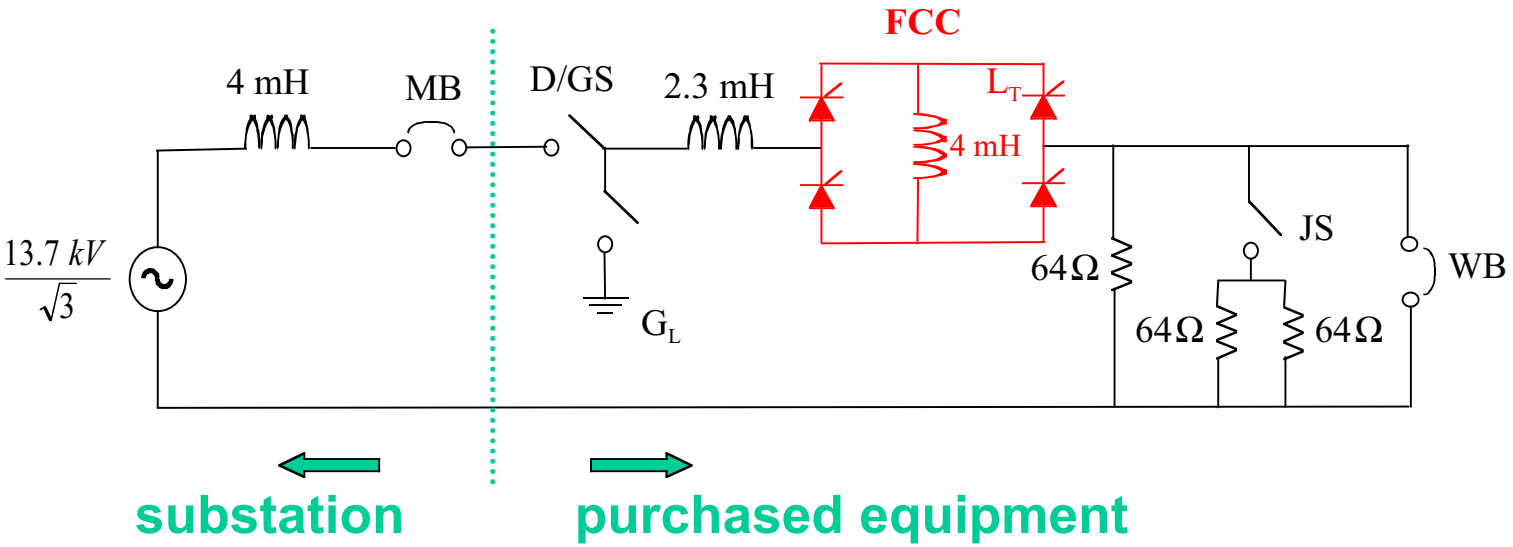
- Power electronics had not been fully tested before
- Demonstrate:
  - bias power supply not needed
  - response to load changes, short circuit, current limiting
- Done in parallel with HV bus redesign
- Use copper coil to simulate HTS coil
- Perform single-phase tests at LANL 13.7 kV substation
- All tests were successful !!

Cryogenics and Vacuum System Preparations

- fan mounts adjusted
- 6” vacuum port added
- both systems operated flawlessly

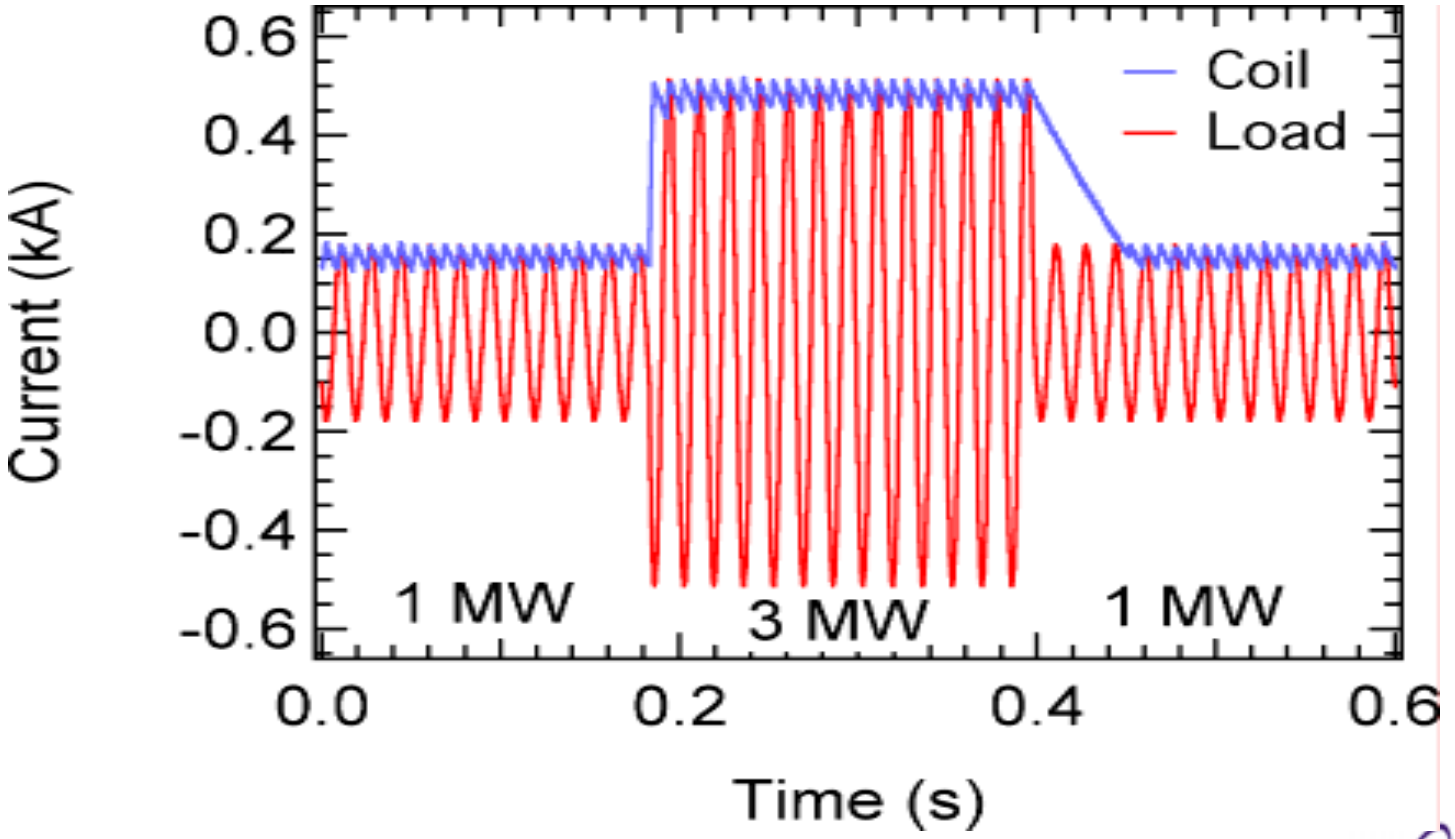
Single-phase Substation Tests of FCC

- Voltage withstand
- Load tests
  - : 1 MW
  - : 1 MW to 3 MW to 1 MW
- Short circuit tests (current limiting)



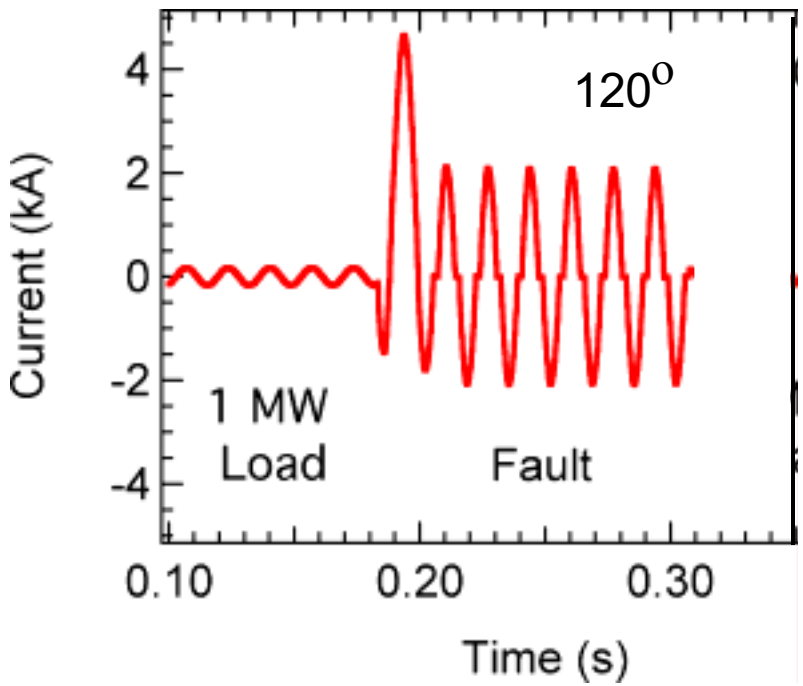
Load Step Test

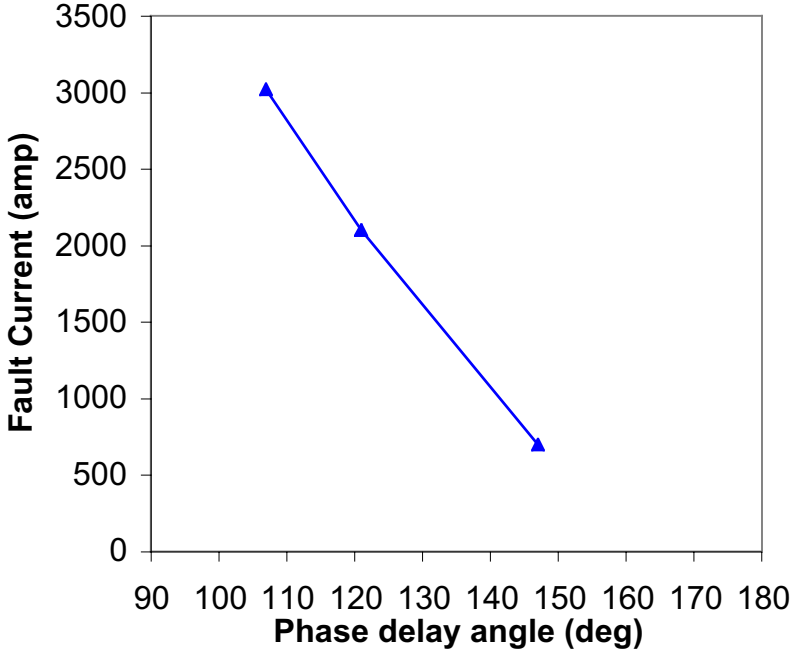
- FCC not affected by load changes
- Coil current: responds to change in load; is mainly DC



Fault Current Limiting Tests

- FCC responds within a few cycles
- Fault current can be controlled from 0 to full current





Test Results Summary

- Successfully demonstrated:
  - vacuum system
  - cryogenic system (magnet cooled to 28 K)
  - control system/FCC
    - no bias power supply
    - voltage withstand
    - steady load
    - load steps
    - fault current control (phase delay angle)
    - solid state breaker

Results Will Be Published

to be presented/published in ***IEEE Power Engineering:***

The Bridge-Type Fault Current Controller – A New FACTS Controller

Heinrich J. Boenig, *Member, IEEE*, Charles H. Mielke, Burt L. Burley, Hong Chen, Joseph A. Waynert, *Senior Member, IEEE*, and Jeffrey O. Willis

to be presented/published in ***Applied Superconductivity Conference:***

Restoration and Testing of an HTS Fault Current Controller

Joseph A. Waynert, *Senior Member, IEEE*, Heinrich J. Boenig, *Member, IEEE*, Charles H. Mielke, Burt L. Burley, and Jeffrey O. Willis

Texas Tech University article on the high voltage testing of the aluminum nitride to be published in ***IEEE 2002 International Power Modulator Conference***

HV Bus Development Capability

HV bus to cold head interface is common to many superconducting devices

- FE electrostatics analysis
- CAD solid modeling
- Prototype fabrication
- Prototype testing
  - hipot room temp and air
  - thermal cycling
  - hipot in vacuum
  - hipot in vacuum and low temperature
  - HV testing with 10 kV, 1.6 MJ flexible capacitor bank
  - testing in LANL 13.7 kV substation

FY02 Performance

Comparison with plans from FY01 Peer Review presentation

- ✔ Complete design, fabrication, and test of new HV bus
- ✔ Demonstrate enhancements of cryogenic and vacuum systems
- ✔ Verify power electronics system performance in LANL substation
- • Evaluate HTS coil performance in capacitor bank tests*
- ✔ Perform single-phase and three-phase* substation tests of FCC

* 2nd quarter program agreement with DOE did not support cost and schedule for capacitor bank testing nor 3-ϕ testing

All plans, as agreed to with DOE, completed !!

FY02 Results

- New HV bus designed/analyzed, fabricated, tested, and integrated into FCC vessel
- Voltage breakdown testing of AlN performed (Texas Tech University), mitigation methods suggested and evaluated
- Installed HV bus performs successfully in LANL substation tests
- Cryogenics and vacuum systems
  - revived and made operational
  - 6” port with gate valve and 350 L/s turbo pump added to vacuum vessel
  - compressor fan mounts repaired
  - RGA data taken w/o charcoal adsorber

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FY02 Results - cont.

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- All components (resistors, inductors, switches, cabling) for single-phase substation testing of FCC in LANL substation were specified, ordered, assembled, and tested
- Control system and power electronics operations verified with copper coil test in LANL substation
- Performed single-phase testing of FCC in LANL substation demonstrating response to load changes, faults, and controllability of fault current
- All tests successful !!

FY03 Plans

Tasks Leading to
Full 3-ϕ Testing at Utility Test Substation

- Jul '02 - Dec '02 Modify cold head/AlN Interface
- Dec '02 - Mar '03 Modify Remaining Two FCC Vessels
- Mar '02 - Apr '03 Test 3-ϕ FCC at LANL Substation
- May '03 - Jun '03 Test 3-ϕ FCC at Utility Test Substation

Estimated cost $800 k - *not presently funded*

Followed by: Reliability and Component Testing at LANL substation